Detection of Local Cracking Damage of in-Service Concrete by AE and X-ray CT

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ABSTRACT

As a detailed inspection of a concrete structure in service, core samples are usually drilled out and then mechanical properties are measured. In this study, damage estimation of structural concrete from concrete-core samples is developed, applying acoustic emission (AE) method. By the authors, the quantitative damage evaluation of concrete has been proposed, by applying AE and damage mechanics in the compression test. The procedure is named **DeCAT** (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique), which is based on the rate process analysis and is applied to theoretically estimate the intact modulus of elasticity in concrete. Prior to the compression test, distribution of micro-cracks in a concrete-core sample is inspected by helical X-ray computer tomography (CT). Then, freeze-thawed damaged samples are tested by the compression test. Concrete-core samples were taken out of a water canal which is extremely developed cracking damage. Thus, it is demonstrated that the concentration of material damage could be evaluated by comparing geometrical characteristics of cracks with the “rate” of AE generation, which is analyzed by AE rate process. A relation between AE rate and damage parameters is correlated in the DeCAT system, and thus the damage of concrete is quantitatively estimated.

INTRODUCTION

The durability of concrete structures decreases easily due to such environmental effects, as freeze-thawed process (JCI-C65, 2005). The degree of damage in concrete is, in most cases, evaluated by an unconfined compression test or ultrasonic test. For effective maintenance and management of concrete structures, it is necessary to evaluate not only the strength of mechanical properties but also the degree of damage. Quantitative damage evaluation of concrete is proposed by applying acoustic emission (AE) method and damage mechanics (Ohtsu and Suzuki, 2004; Suzuki *et al*., 2007). The procedure is named **DeCAT** (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique), which is based on estimating an intact modulus of elasticity in concrete (RILEM TC-212ACD, 2010; Suzuki *et al*. 2010; Suzuki and Othsu, 2014a).

In this study, damage estimation of structural concrete from concrete-core samples is developed, applying DeCAT system. Concrete-core samples taken from reinforced concrete of an existing concrete canal wall were tested. These samples were strongly influenced by freeze-thawed process (Suzuki *et al*. 2010). The crack distribution of concrete was inspected with helical CT scans. After helical CT scan, damage of freeze-thawed samples was evaluated, based on fracturing behavior under unconfined compression with AE. The AE generation behavior is associated with crack volume responsible for damage in concrete. The decrease in physical properties could be evaluated by comparing geometrical characteristics of cracks with AE generation behavior in compression test. These values are affected by the internal actual cracks. Thus, the damage of concrete could be quantitatively evaluated by damage parameters based on detected AE.

ANALYTICAL PROCEDURE

AE Rate-Process Analysis

The AE activity of a concrete core under compression is associated with the rate process theory which was introduced (Ohtsu and Suzuki, 2004). In DeCAT system, detected AE waves are treated by AE rate-process analysis. AE behavior of a concrete sample under compression is associated with the generation of micro cracks. These cracks tend to gradually accumulate until final failure. Since this process could be referred to as stochastic, the following equation of the rate process is introduced to formulate the number of AE events, dN, due to the increment of strain from ε to $\varepsilon+d\varepsilon$,

$$f(\varepsilon)d\varepsilon = \frac{dN}{N}, \tag{1}$$

where N is the total number of AE events and $f(\varepsilon)$ is the probability function of AE at strain level ε %. For $f(\varepsilon)$ in **Eq. 1**, the following exponential function is assumed,

$$f(\varepsilon) = \alpha \cdot \exp(\beta\varepsilon), \tag{2}$$

where α and β are empirical constants. Here, the value β is named the rate (**Fig. 1**). The probability varies in particular at low strain level, depending on whether rate β is positive or negative. If rate β is negative, the probability of AE events is high at low strain level. This indicates that the testing concrete may be damaged. If the rate is positive, probability is low at low strain level and the concrete is in stable condition. Therefore, it is possible to quantitatively evaluate the damage in a concrete using AE under uniaxial compression by AE generation behavior. In this study, quantitative damage evaluation of freeze - thawed concrete are analyzed by comparison of AE 'β' and X-ray CT 'C_i'.

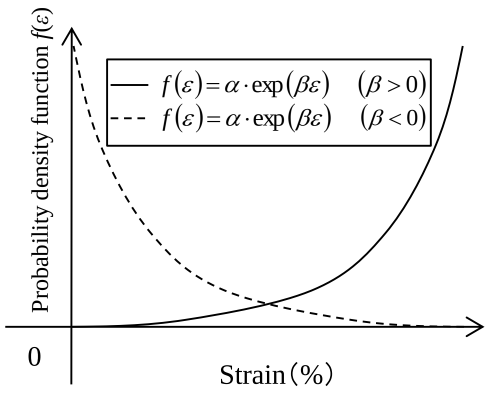


Fig. 1 Two possible relations of probability function $f(\varepsilon)$.

Damage Mechanics for Quantification of Cracking Effects in Concrete

The concrete damage is defined as decrease of effective area in cross-section (Kochanov, 1986), which is able to be detected by X-ray CT test. Quantification of concrete damage is performed using X-ray CT images which is analyzed by spatial statistics parameters with damage mechanics (Suzuki and Ohtsu, 2014b; Suzuki and Shiotani, 2015).

Damage parameter Ω in continuum damage mechanics is defined as a relative change in the modulus of elasticity, as follows,

$$\Omega = 1 - \frac{E}{E*}, \tag{3}$$

where E is the modulus of elasticity and E^* is the modulus of concrete which is assumed to be intact and undamaged. Loland (1989) assumed that the relationship between damage parameter Ω and strain ε under uniaxial compression is expressed,

$$\Omega = \Omega_0 + A_0\varepsilon^{\lambda}, \tag{4}$$

where Ω_0 is the initial damage at the onset of the uniaxial compression test, and A_0 and λ are empirical constants of the concrete. The following equation is derived from Eqs.3 and 4,

$$\sigma = (E_0 - E * A_0\varepsilon^{\lambda})\varepsilon. \tag{5}$$

The damage of concrete is evaluated by damage parameter "λ". The equation of λ is expressed (**Fig. 2**),

$$\lambda = \frac{E_c}{E_0 - E_c}. \tag{6}$$

In this study, accumulation of concrete damage is evaluated by damage parameter "λ", detected AE and X-ray CT image. The X-ray CT parameters are based on quantification of detected CT numbers, which is obtained in Hounsfield Units (HU) represents the mean X-ray absorption associated with each area on the CT image. The CT numbers vary according to the material properties (i.e. crack concentration of concrete), generally adjusted to 0.0 for water and to -1,000 for air. The detected X-ray CT images are analyzed by roundness parameter C_i which is defined as spatial statistics parameter for quantitative evaluation of characteristics of geometric properties. The following equation of roundness parameter C_i is introduced to formulate the ratio of the area of cracking damage, A, and these round length P,

$$C_i = \frac{P^2}{A}. \tag{7}$$

The roundness parameter C_i is analyzed by binary treatment of X-ray CT image (threshold level: 73, average max value). The crack detection accuracy is approximately 200μm in each X-ray CT images.

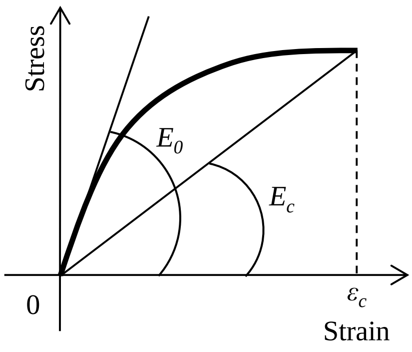


Fig. 2 Stress-strain relation and determination of Young's modulus.

EXPERIMENTAL PROCEDURE

Specimens

Cylindrical samples of 5cm in diameter and about 10cm in height were composed of taken from the freeze-thawed damage structures which is constructed after about 40 years (**Figs. 3** and **4**). Test samples are classified into three types by cracking damage conditions based on X-ray CT image characteristics (see **Fig. 4**). The heavy cracked core-sample is named “Type A”. The little cracked core-samples are named “Type B”. The normal samples are named “Type C”. These samples are comparison of mechanical properties, X-ray CT parameter and AE.

Fig. 3 Overview of local crack distribution of core sampling wall.

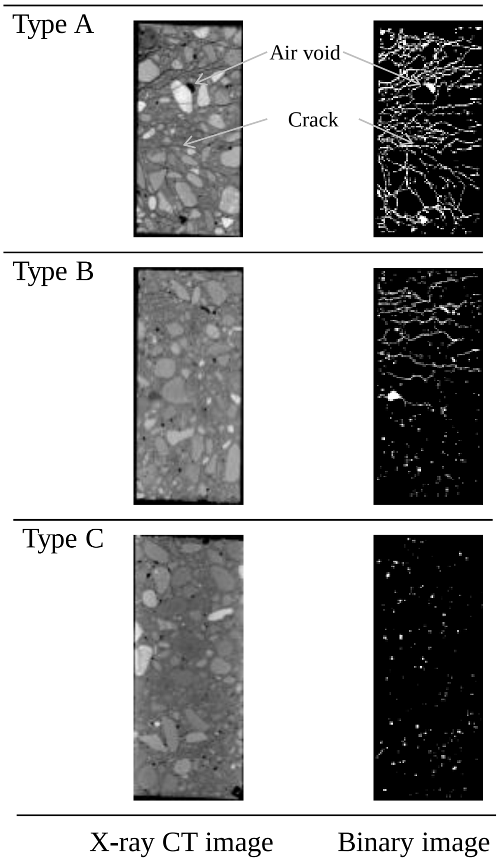


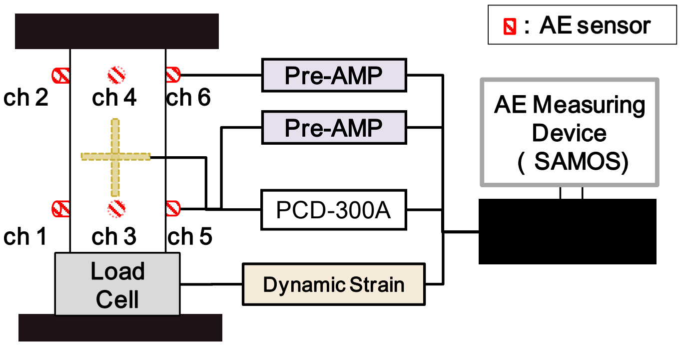
Fig. 4 X-ray CT and binary image of testing samples.

Visualization of cracked damage using X-Ray CT Images

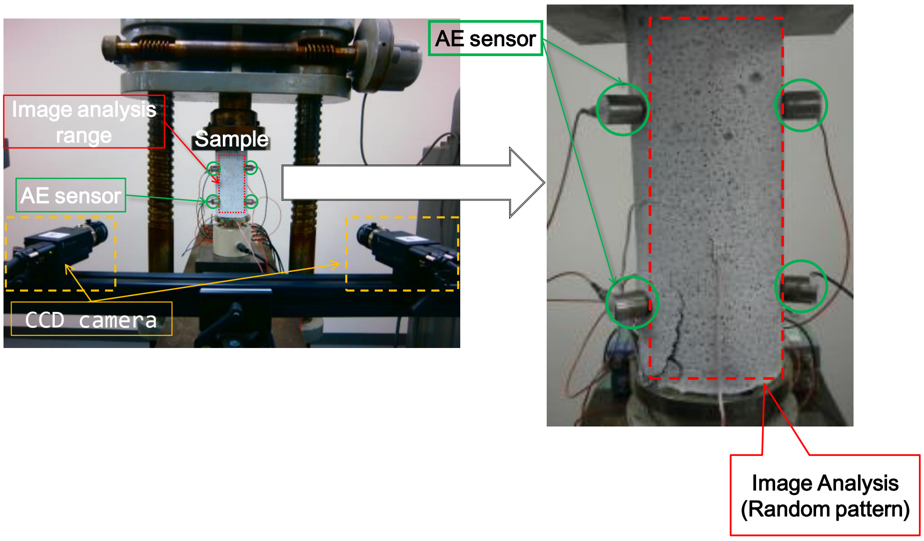
The cracked core samples were inspected with helical CT scans at the Medical Center, Niigata University. The helical CT scan was undertaken at one-millimeter intervals before the compression test. The measurement conditions are shown in **Table 1**(Suzuki and Ohtsu, 2014b; Suzuki and Shiotani, 2015). The output images were visualized in gray scale where air appears as a dark area and the densest parts in the image appear as white. The exact positioning was ensured using a laser positioning device. Samples were scanned constantly at 0.5mm pitch overlapping. A total of 200 to 400 2D-images were obtained from each specimen depending on the specimen length. These 2D images can be assembled to provide 3D representation of core specimens.

Table 1 Setting used for helical CT scan.

Helical Pitch	15.0
Slice Thickness	1.0mm
Speed	7.5mm/rotation
Exposure	120kV and 300mA
Recon Matrix	512×512
Field of View	100-200mm



(a) AE monitoring



(b) Image analysis using DICM

Fig.5 Test setup for AE and DICM monitoring in compression test.

Fracture monitoring by AE in core test

After the ultrasonic test and X-ray CT measurement, the compression test was performed, measuring AE activities and stress-strain relation. The AE monitoring was conducted by employing AE sensor of 150 kHz resonance (R15α, PAC) which was attached at the 6 part of the specimen (**Fig. 5 (a)**). Amplification was 60 dB gains in total. The frequency range was set from 60 kHz to 1 MHz. AE hits were detected at threshold level 42 dB by an AE system (SAMOS-AE, PAC). The strain monitoring was conducted by DICM in core test (**Fig. 5 (b)**).

RESULTS AND DISCUSSION

Mechanical Properties of Testing Concrete

The mechanical properties of testing samples are shown in **Table 2**, with the maximum and the minimum values of all specimens. 6 samples are strongly influenced by freezing and thawing effect.

The compressive strength is 7.0 N/mm^2 in the heavy cracked condition (Type A), while that of the non-cracked condition is 27.9 N/mm^2 as the average (max: 27.6 N/mm^2, min: 28.2 N/mm^2). Thus, the decrease in the mechanical properties is clearly observed in Type A. On the other hand in the little cracked condition (Type B), the compressive strength is 5.1 N/mm^2 as the average (Type B<Type A<Type C). The damage parameter λ is detected 0.64 in Type A. In Type B and C, increase trend of average λ is detected.

AE generating behavior in core test is evaluated by AE parameter β. Type A and Type B samples are evaluated the negative β value in AE rate-process analysis (Type A: -1.4×10^{-2}, Type B: -0.5×10^{-2} (average)). The rate β is negative; the probability of AE activity is high at a low strain level in compression test. It is indicating that the sampling structure is developed by heavy freeze-thawed damage. Therefore, these results is suggested that the sampling structure is developed local damages and damage level is qualitatively evaluated by AE parameter β.

Table 2 Mechanical propertied of testing core samples.

	Compressive strength (N/mm^2)	Maximum strain (μ)	Tangent modulus of elasticity (GPa)	AE parameter β (β<0.0: Damage)	Damage parameter λ	Sample size
Type A Heavy Cracked Concrete	7.0 [-]	3,000 [-]	5.9 [-]	-0.014 [-]	0.64 [-]	1
Type B Little Cracked Concrete	5.1 [3.8~7.3]	2,783 [1,060~3,365]	2.9 [0.2~5.6]	-0.005 [-0.009~-0.0003]	2.85 [1.23~5.53]	3
Type C Non-Cracked Concrete	27.9 [27.6~28.2]	1,250 [1,050~1,450]	35.8 [27.7~43.9]	+0.015 [+0.014~+0.016]	1.89 [1.58~2.20]	2

Average [Max-Min]

Evaluation of Concrete Damage using X-ray CT Image

The X-ray CT data is analyzed by the roundness parameter C_i which is defined as the spatial statistics parameter. Analytical results are shown in **Table 3**. The roundness parameter C_i is calculated from X-ray CT image with binary treatment. In Type A, C_i is detected 78.6 on the average, with 47,548 at the dispersion. On the other hand, Type B is 26.1 on the average, which is 0.33 times lower than Type A sample. In Type C, average C_i is detected 13.7, which is 0.17 times lower than Type A sample. Frequency of C_i value is shown in **Fig. 6**. The C_i value is frequently detected 40 under value in all type samples. This is because, these evaluated C_i is affected by distribution of normal air void characteristics. In Type A sample, range of C_i is distributed in 200 or more over. Comparison of Type A and Type C, analytical C_i range is detected concentration of 10 to 20. The average C_i value is compared with air void ratio in **Fig. 7**. It can be clearly separated in each sample type by using relation between average C_i and air void ratio. Our recent studies, the concentration of crack damage in concrete was positively correlated with decrease trend of CT value (Suzuki et al., 2010). Thus, the results of Type A and Type B are plotted in high C_i value part ($C_i > 20$), it is considered that these samples have been fairly damaged.

Table 3 Air void and crack properties of testing core samples.

Sample Type	Aspect ratio (-)	Roundness (-)	Ares (mm^2)	Void perimeter (mm)	CT value (-)	Air void ratio (%)
Type A	3.46 (6.62)	78.62 (47,548)	13.2 (2,499.6)	30.9 (10639.3)	1,557.9 (104,554.5)	11.4
Type B	2.68 (4.91)	26.14 (1,742)	3.4 (127.6)	8.3 (413.6)	1,617.1 (66,429.1)	4.8
Type C	1.66 (0.63)	13.66 (31)	1.8 (7.2)	4.3 (9.4)	1,662.1 (52,982.9)	1.0

Average (Dispersion)

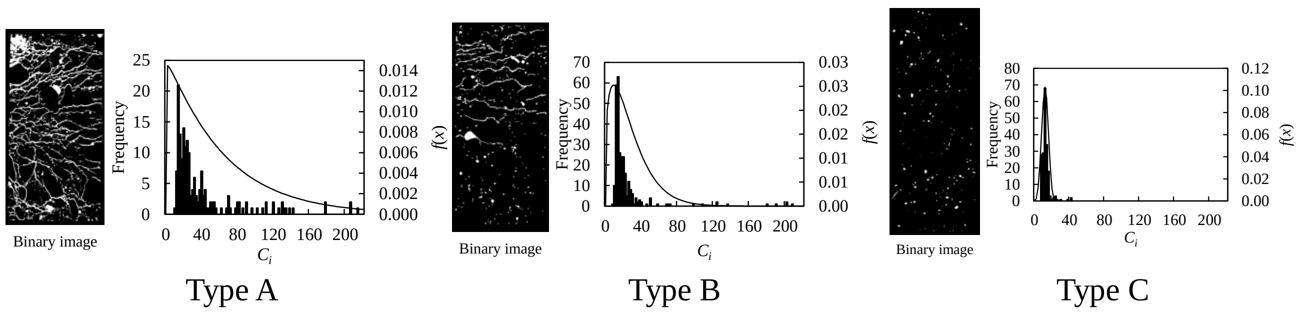


Fig. 6 Characteristics of roundness parameter C_i in Type A, B and C.

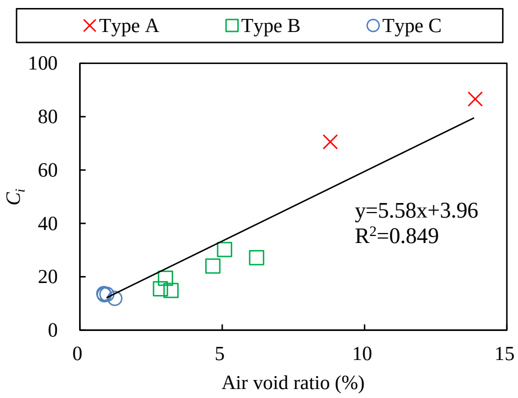


Fig. 7 Relation between roundness parameter C_i and air void ratio.

AE generation behavior in core test

Mechanical properties are summarized in **Table 2**, with average and range of detected values of all specimens. The AE generation behavior in core test is shown in **Figs. 8** and **9**.

In **Fig. 8**, it is clearly observed that compressive fracture process of damage concrete (Type A and B) appeared increase trend of low amplitude AE (42-59dB) which is generated from friction of inner cracks. On the other hand, non-cracked concrete (Type C), high amplitude AE was frequently detected in core test. As discuss in the previous researches, increase of low energy AE can be thought of 'Secondary AE' which is generated from inner damaged part, such as cracks (JSNDI, 2006).

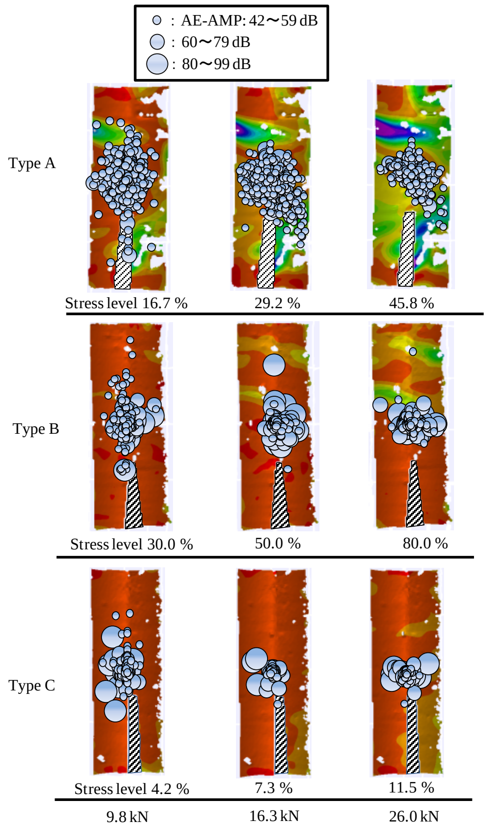


Fig.8 Characteristics of AE generation behavior in core test.

In **Fig. 9**, comparison of AE generation behavior in fracture process by non-damaged and freeze-thawed conditions. In general of AE rate process theory, concrete damage condition is defined as detection of high AE generation behavior in low strain level. Non-damaged concrete sample was detected low AE probability function $f(\varepsilon)$ in low strain level. In Type B, little cracked concrete was detected high AE probability function $f(\varepsilon)$ in low strain level. AE generating behavior of Type A and B showed the negative β in AE rate-process analysis (β<0.0, damage condition) which was fairly damaged by freeze-thawed process. So, all the freeze-thawed samples (Type A and B) are found to be damaged. These results of $f(\varepsilon)$ suggest that decreasing trend of β value is in good agreement with the increase in damage. Thus, the results of damage estimation using AE is useful for concrete structure.

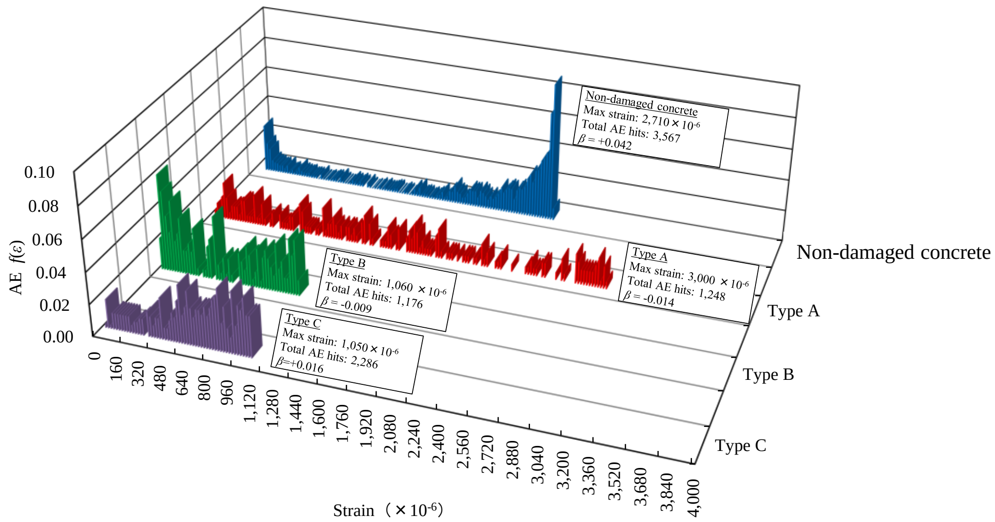


Fig. 9 Comparison of AE generation behavior by non-damaged concrete and freeze-thawed samples.

Damage Estimation by AE and X-ray CT parameters

The accumulation of crack damage in testing samples is positively correlated with decrease trend of 'C_i' and 'β'. The damage index β and P-wave velocity are compared with C_i in **Fig. 10**. In β<0.0 condition, AE generation behavior is high at low strain level. This results indicates that the testing concrete may be damaged. The P-wave velocity is detected same trend of AE index β in core test. The standard of P-wave velocity in concrete is defined as 4,000m/s (JSNDI, 1994). The decrease trend of P wave velocity is correlated with inner damage (JSCE, 2004). In β=0.0 condition, estimated P-wave velocity is analyzed about 3,053m/s (<4km/s, 76.3%=3,053/4,000). Therefore, these results detect that negative value of β with the increase in damage. And, AE index in core test is estimated by non-destructive P-wave monitoring.

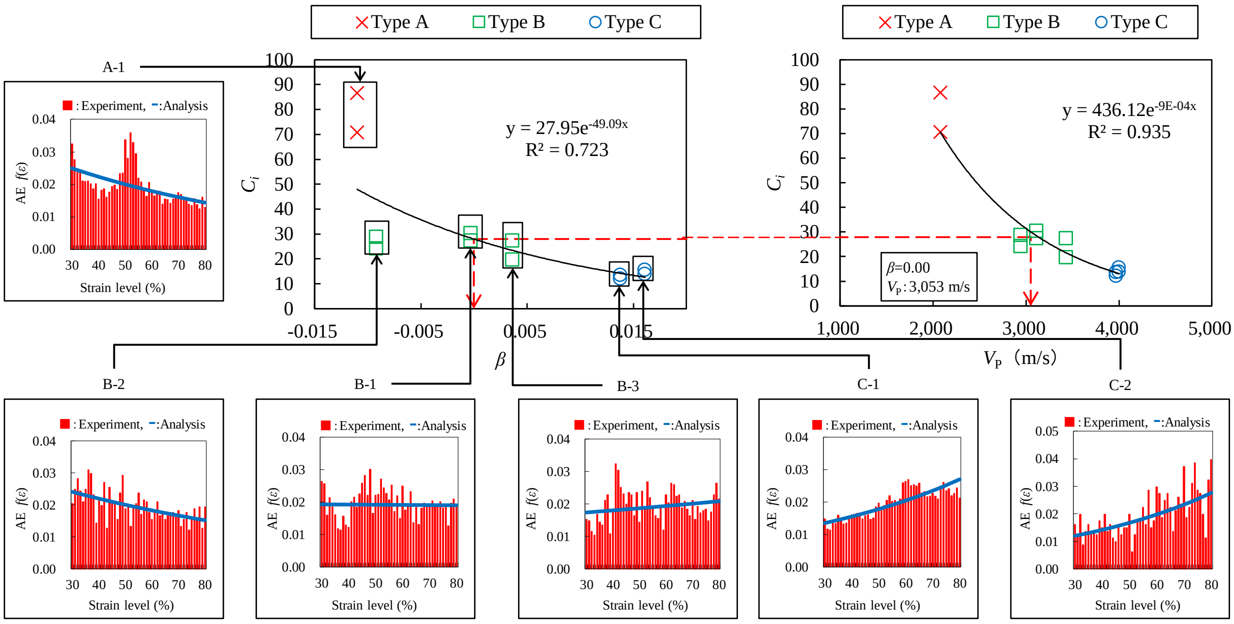


Fig. 10 Relation between AE parameter β and P-wave velocity.

CONCLUSION

For quantitative estimation of damage in concrete, AE monitoring is applied to the uniaxial compression test of concrete samples. Analytical procedure is based on the rate-process theory. In this study, AE rate-process analysis is applied to damage estimation of concrete-core samples taken from a concrete water-canal which is affected by freeze-thaw process. It is quantitatively demonstrated that testing concrete-core samples are damaged. In addition, applying the X-ray CT test, spatial distribution of the cracking damage in core sample is readily determined. Reasonable agreement with spatial distribution of cracks in concrete is confirmed by the results of AE generation behavior in core test. The results are summarized as follow.

(1) To assess the damage of concrete subjected to freeze-thawed effects, a method to monitor AE generation behavior of core samples under uniaxial compressive loading was investigated. The degree of damage was evaluated using AE parameter β.

(2) From the results of core samples taken out of a deteriorated concrete canal, it is confirmed that with the decrease in evaluation parameters β, C_i of the micro-cracks responsible for the concrete

damage. This demonstration that AE parameter β could give a qualitative reference on damage level of concrete.

(3) The AE parameter β is an obtained as a damage index in core test, while the P-wave velocity is determined by UT. These experimental values was correlated with X-ray CT parameter C_i.

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